

Space Transportation Main Engine Configuration Study

Contract NAS 8-36867

Configuration Evaluation And Criteria Plan (DR-9)

Volume 1: System Trades Study And Design
Methodology Plan

August 1986

Prepared For:

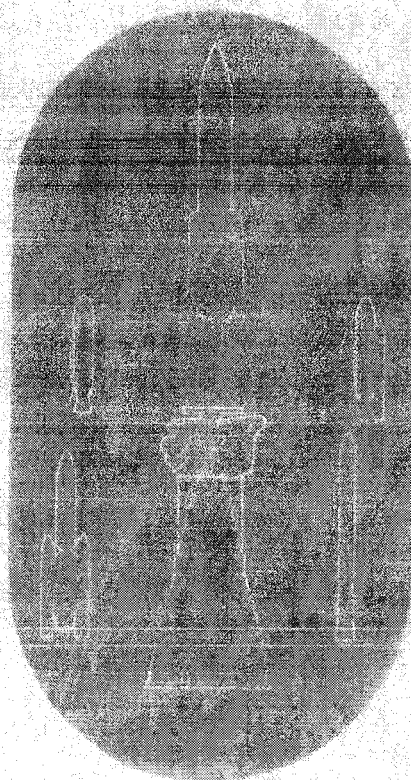
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CONFIGURATION EVALUATION AND CRITERIA PLAN
VOLUME 1 - SYSTEM TRADES STUDY AND DESIGN METHODOLOGY PLAN
(PRELIMINARY)

SPACE TRANSPORTATION MAIN ENGINE
(STME) CONFIGURATION STUDY

Contract NAS 8-36867

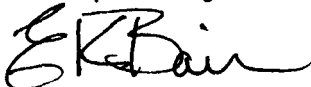
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FOREWORD

This is the System Trades Study and Design Methodology Plan for the Space Transportation Main Engine Configuration Study and has been prepared as part of Task 2.0 of Contract NAS 8-36867. The work is being performed by the Aerojet TechSystems Company for the NASA - Marshall Space Flight Center.

The program objective is to identify candidate Main engine configurations which enhance launch vehicle performance, operation and cost. These candidate configurations will be evaluated and the configuration(s) which provide significant advantages over existing systems will be selected for consideration for the next generation launch vehicles.

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The System Trades Study and Design Methodology Plan is Volume 1 of the Configuration Evaluation and Criteria Plan, Contract Data Requirement DR-9. Volume 2 is the Evaluation Criteria Plan.

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I. INTRODUCTION

The System Trades Study and Design Methodology Plan is used to conduct trade studies to define the combination of engine features that will optimize candidate engine configurations. This is accomplished by using vehicle sensitivities and engine parametric data to establish engine chamber pressure and area ratio design points for candidate engine configurations.

Engineering analyses are to be conducted to refine and optimize the candidate configurations at their design points. The optimized engine data and characteristics are then evaluated and compared against other candidates being considered. The Evaluation Criteria Plan, Volume 2 of DR-9, is then used to compare and rank the optimized engine configurations on the basis of cost.

II. SYSTEM TRADE AND DESIGN METHODOLOGY PLAN (TASK 2.0)

The Engine Design Process is shown in Figure 1. This three step process is initiated on a broad basis which considers all of the aspects of an engine/vehicle trade study. The resulting candidate selections are then optimized before being subjected to the evaluation and selection process. The configuration identified by this effort is then carried forward into the conceptual design effort. The resulting engine design is a complete conceptual definition which addresses integration and packaging and is supported by preliminary ICD's and CEI documents.

The requirements for the engine are determined by Space Transportation Architecture Study, (STAS) results along with specified contractual requirements.

The specified baseline requirements include:

- Two Engines/Vehicle
- Eight Vehicle Fleet
- LOX/LH₂ Propellants
- 100 Mission Life
- 520 Second Burn Time Per Mission
- Closed Loop Thrust/MR Control
- Throttling Capability (Range TBD)
- Gimballing Capability for TVC
- Two Position Nozzle, $\epsilon = 50$ to 150
- Sea Level and Altitude Start Capability
- Single or Multiple Engine Application
- Expandable or Reusable

A. ENGINE/VEHICLE TRADE STUDIES (SUB-TASK 2.1)

The engine to vehicle trade relationships are based on STAS sensitivity data and weighting relationships derived from engine performance and weight.

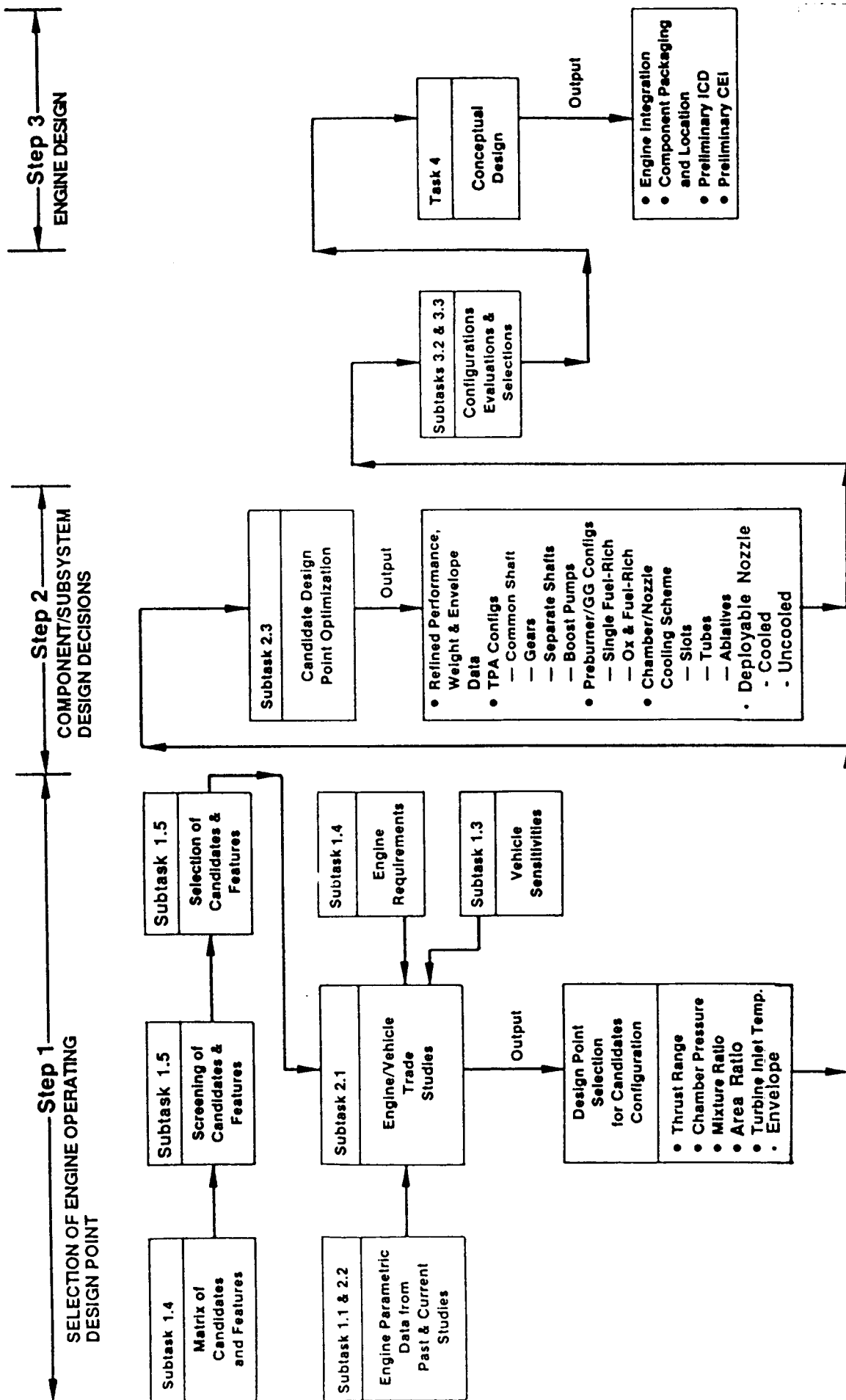


Figure 1. Engine Design Process

II, A, Engine/Vehicle Trade Studies (Sub-Task 2.1) (cont.)

The STAS models call for a two engine, 580000 lbf thrust per engine, propulsion system to operate over a 520 second mission burn. The value, or cost, of placing one pound in low earth orbit (LEO) was established at \$500/lb. Launch weight variances due to performance and engine weight are charged directly against payload capability on a one for one basis at the \$500/lb rate.

Propellant weight to performance variation is determined by using a modified version of the basic ΔV equation.

The ΔV (required to LEO is ≈ 25500 ft/sec) is modified to account for gravity, drag and thrust losses as a function of the GLOW/Thrust ratio. A liftoff thrust to weight ratio of 1.3 is assumed for this effort with a resulting $\Delta V'$ of 32000 ft/sec being required, see Figure 2.

The vehicle is a two stage parallel burn design with staging at 130 seconds and a velocity of 6000 ft/sec. On this basis the remaining ΔV to LEO is: $32000 - 6000 = 26000$ ft/sec. This value is used in the basic ΔV equation; where:

$$\text{Weight at Burnout} = \text{Initial Weight (at 6000 ft/sec)} \\ \times \exp \left(\frac{-\Delta V}{g \times I_{sp}} \right)$$

and: $\Delta V = 26,000$ ft/sec

$$g = 32.2 \text{ ft/sec}^2$$

$$I_{sp_{\text{nominal}}} = 465 \text{ sec (vacuum @ } \epsilon = 150)$$

The effect of a change in I_{sp} is evaluated by plugging in the new I_{sp} and comparing the change in burnout weight against the optimum case. This weight difference is charged as a one for one trade with payload.

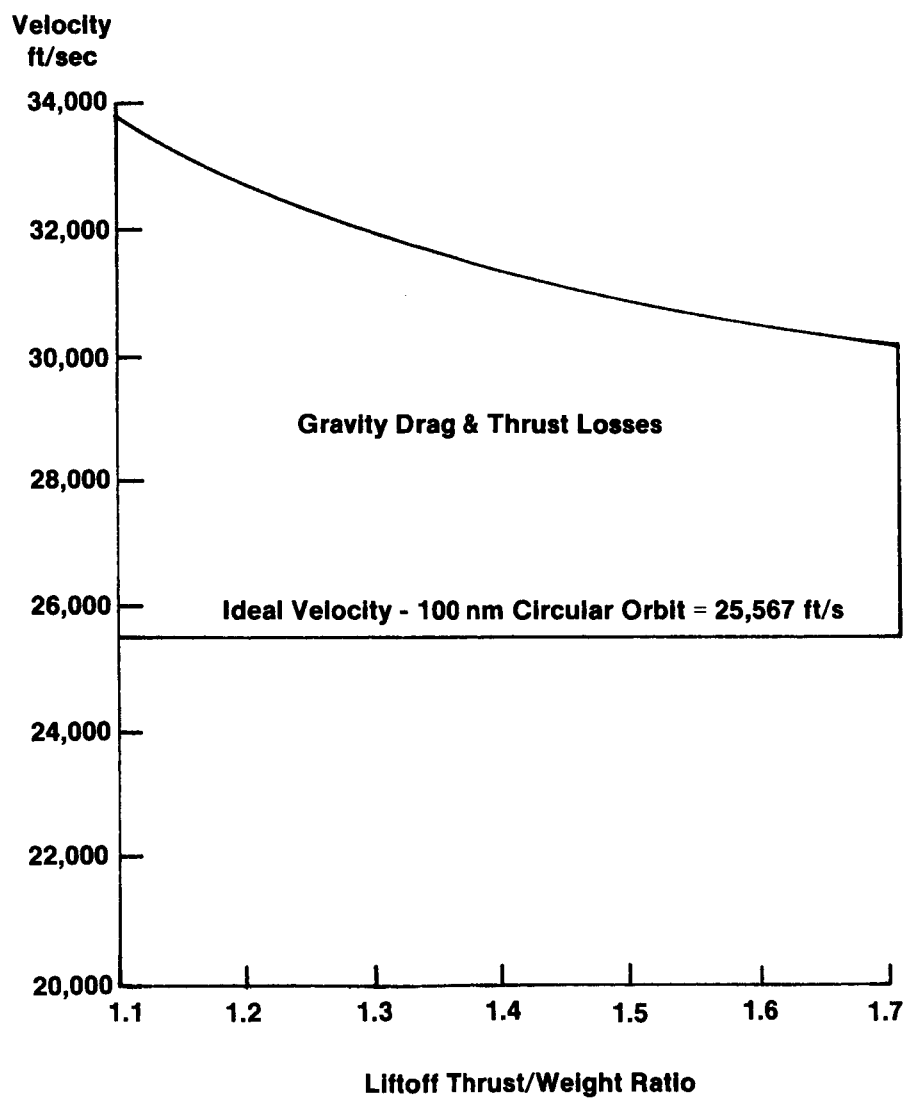


Figure 2. ΔV Modification for Simplified LEO Propulsion Requirements

II, A, Engine/Vehicle Trade Studies (Sub-Task 2.1) (cont.)

Differences in engine weight are handled as a straight forward one for one trade against payload.

Since engine performance and weight can be directly related to vehicle and mission performance they serve as the comparative link between the engine candidates and the mission model; the comparison is reduced to a cost difference relationship.

B. ENGINE PARAMETRIC STUDIES (SUB-TASK 2.2)

Preliminary engine concepts will be examined using the models developed for the STAS studies. This family of models is capable of analyzing gas generator, stage combustion and dual nozzle engine cycles. Performance is estimated using the JANNAF Simplified Performance Prediction Procedure.

Inputs to the model include:

- Thrust
- Mixture Ratio
- Chamber Pressure
- Area Ratio and Exit Pressure
- Idealized Performance (S.L. and Vacuum)
- Efficiencies: TCA and TPA's
- Turbine Temperatures
- Propellant Properties
- Basic TCA and Chamber Dimensions

Outputs include:

- Performance
- Envelope Sizing
- Weight
- Component Sizing

II, B, Engine Parametric Studies (Sub-Task 2.2) (cont.)

System state point conditions are estimated and by iterating the model input the design point can be refined.

The performance and weight estimates for the candidate concepts provide the inputs necessary to conduct the mission/vehicle/engine comparisons discussed in Section A, Engine/Vehicle Trade Studies.

C. CANDIDATE DESIGN POINT OPTIMIZATION (SUB-TASK 2.3)

Optimization of the engine candidates is an iterative process which includes: 1) the design point selection and 2) engine component design analysis and optimization.

The engine design point is refined and selected by iterating the basic engine parameters of: chamber pressure, area ratio and turbine inlet temperature using the STAS models as previously described in Section B.

The candidate engines are defined by the cycles and arrangements (input) and the resulting performance, weight and envelope determined by the STAS models.

In order to substantiate the selections the engine designs must be examined and refined at the major sub-assembly or sub-component level. This process is described in the following paragraphs.

1. Chamber/Throat/Fixed Nozzle Design

The chamber/throat/fixed nozzle are sized by the system level analysis conducted with the STAS engine models.

Chamber cooling analysis is conducted using the technique shown in the Figure 3 block diagram.

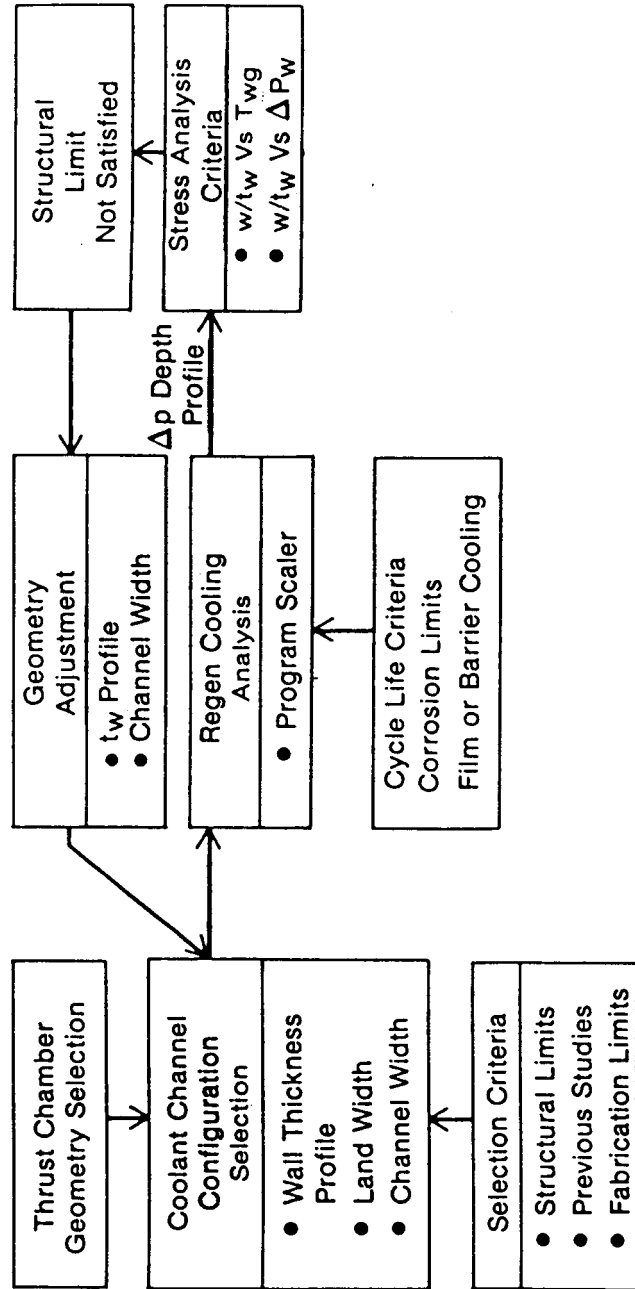


Figure 3. Chamber Cooling Analysis Logic Diagram

II, C, Candidate Design Point Optimization (Sub-Task 2.3) (cont.)

The primary criteria used to generate coolant channel designs consist of allowable pressure drop and low cycle fatigue/creep limits. Low cycle fatigue limits are expressed as allowable gas-side wall temperature vs closeout wall temperature. The maximum allowable gas-side wall temperature is controlled by creep limits, which for copper-based alloy is usually less than 1000°F. Other design criteria will consist of flow distribution and channel fabrication limits.

The regeneratively-cooled chamber designs for the selected configurations will be generated using ATC's SCALER computer program.

This program performs a detailed multistation analysis of a rectangular channel based on scaled chamber geometry and calculated internal and external heat transfer coefficients.

The SCALER program includes an entrainment model for gas film cooling which applies to either fuel film cooling or use of a low mixture ratio barrier. An analysis of a nozzle tube bundle will be performed using the HEAT program, which performs a 1D radial tube analysis using the same methodology as the SCALER program.

Transpiration-cooled throat section analysis will be accomplished using the TRNRG program. This program solves a combined internal fin-coolant energy equation and includes the heat blockage effect due to blowing into the boundary layer.

A thorough combustion stability analysis will be conducted and will entail calculation of combustion time lags, determination of all modes of instability and determination of the type of high frequency acoustic instability: injection-coupled vs intrinsic acoustic. Inputs include combustion time lags, operating conditions and chamber dimensions.

II, C, Candidate Design Point Optimization (Sub-Task 2.3) (cont.)

LFCS2A is used for determination of chug stability limits, ICASE is used for injection-coupled acoustic mode analysis and IFAR is used in the analysis of intrinsic acoustic mode stability.

The method of injection will determine which type of high frequency stability mode is relevant, i.e., intrinsic acoustic or injection-coupled.

The predominant modes of instability will identify the mechanical damping devices required for stable operation.

Preliminary structural analyses will be conducted for the selected designs.

Thrust Chamber Assembly- The effort required for slotted main chambers is one of initially establishing allowable operating pressure and temperature regimes or envelopes. These will aid in trades that will result in a final optimum design that is structurally and functionally acceptable. Figure 4 depicts the logic methodology of establishing allowable sizes to ensure life capability for a regeneratively cooled thrust chamber wall.

For the tube bundle combustion chamber and nozzle designs, preliminary sizing of tube geometry is conducted parametrically by ensuring hoop stress (due to tube internal pressure) does not exceed the allowable hot gas wall temperature tensile yield strength, Figure 5. A geometric structural model will be developed and an analysis conducted.

2. Extendible Nozzle Design

As with the main chamber the extendible nozzle is basically sized using the STAS engine model results. Concepts for this component include radiation, regenerative and dump cooled designs.

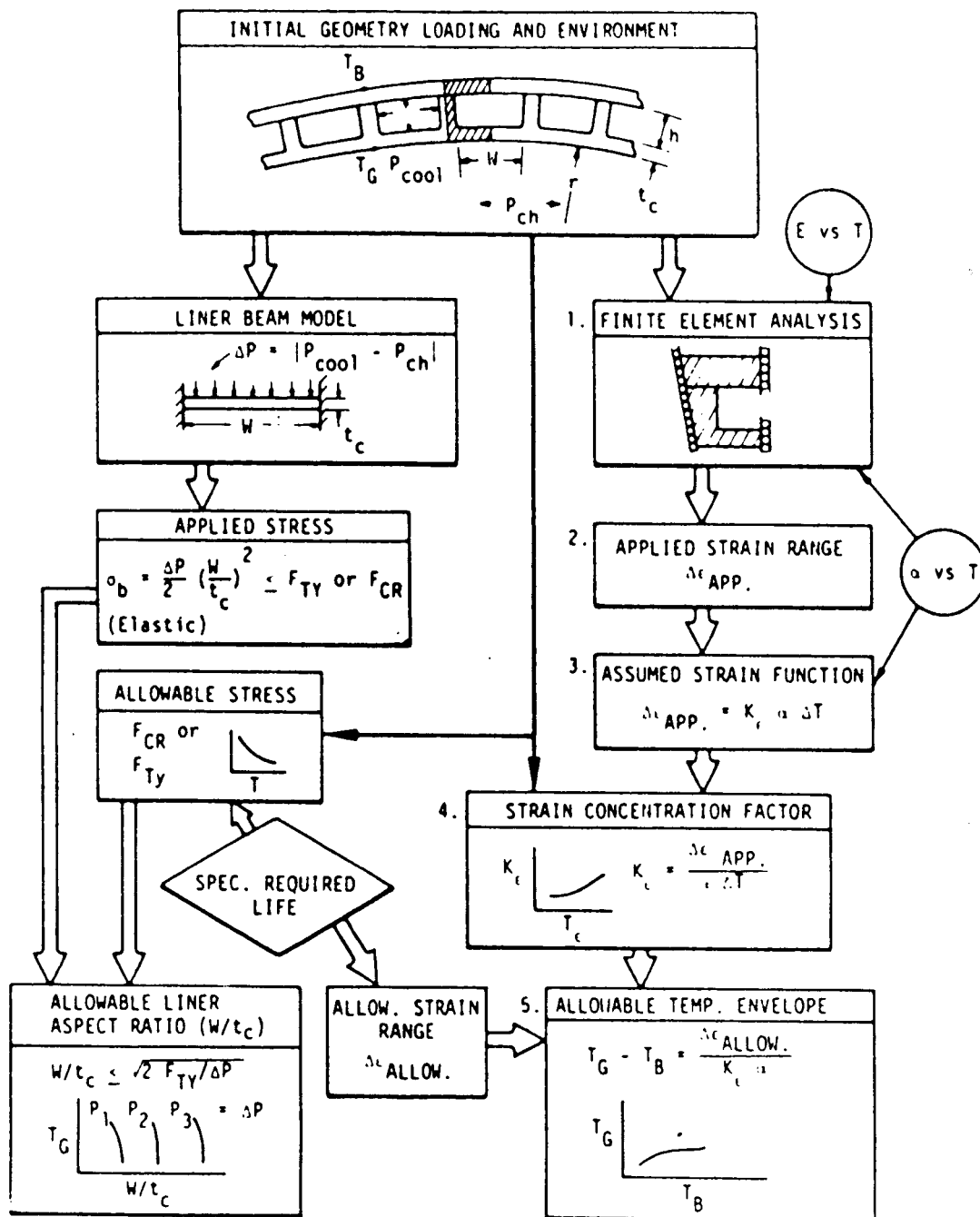


Figure 4. Logic Diagram for Initial Enveloping

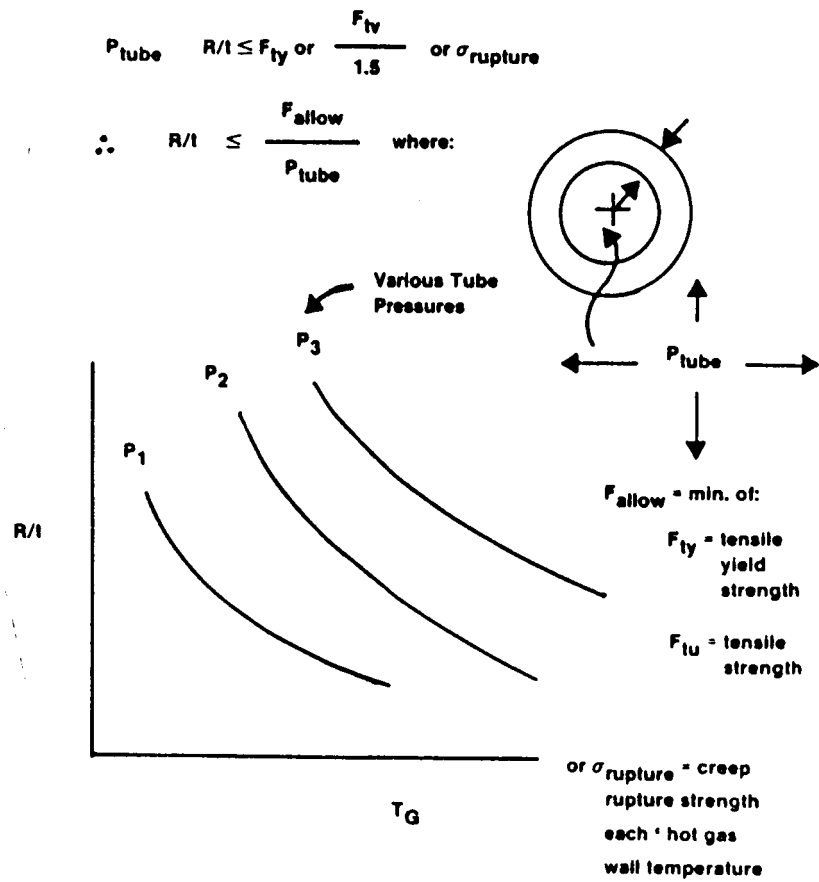


Figure 5. Tube Geometry Sizing Logic

II, C, Candidate Design Point Optimization (Sub-Task 2.3) (cont.)

Cooling requirements are determined for a particular design and their effect on overall engine performance assessed. Methods include (as appropriate) SCALER and other previously applied techniques. In parallel, deployment/retraction concepts are investigated and conceptual designs developed which define complexity, envelope and weight.

The performance and weight influences are evaluated at the engine/vehicle/mission model level using the evaluation criteria developed in Task 3.0.

3. Preburner/Gas Generator

The STAS engine model analysis defines the preburner/gas generator design requirements. The cooling, stability and structural/life analyses are conducted in a manner similar to that described for the main chamber in Section 1 (as appropriate).

In the case of the gas generator the turbines drive gas, which by-passes the main chamber/nozzle, must be assessed for its performance effect at the engine/vehicle/mission model level.

4. Turbomachinery Design

As with the other components the requirements for the low pressure and high pressure turbopumps are derived from the results from the STAS model engine runs. Pump flowrate and pressure rise and turbine flows, pressure and temperature are used to size these components.

Preliminary designs for the turbopumps are developed using the TURBO turbomachine sizing program. This program develops pump and turbine performance data, shaft speed, basic sizing and weight and will be used in the design point optimization process. Additionally bearing and seal requirements are assessed and a conceptual design layout developed.

II, C, Candidate Design Point Optimization (Sub-Task 2.3) (cont.)

The design point performance is used as input into the STAS engine program during the iterative optimization process. Turbomachinery life is considered in three areas: bearing life, seal life and structural integrity and life. The structural considerations include rupture, deformation and yielding and high and low cycle fatigue as they relate to the applied safety factors. Fracture mechanics techniques are applied where flaw growth is a concern.

5. Control Valves

Engine cycle selection will dictate the number and types of control valves required and establishes valve type grouping(s). The basic engine flow, pressure and temperature schedule, derived from the STAS modeling, along with ΔP , leak and control needs establish the valve performance requirements. From the requirements concepts, flow control and actuation trades can be made. The process is shown in Figure 6.

The effects of weight, maintainability and cost are assessed relative to their influence on the engine/vehicle/mission model trade-offs.

6. Engine Operation and Control

The detailed design analysis of an engine controller is not considered to be a requirement of the STME Study; however, controller weight and envelope information will be developed to aid in engine arrangement and interface analysis. Engine control requirements such as throttling, MR control, nozzle deployment and reusability will be considered for the closed loop engine controller.

The preliminary sizing, weight and cost estimates will be used to support the overall engine design and provide supporting data for the engine evaluation.

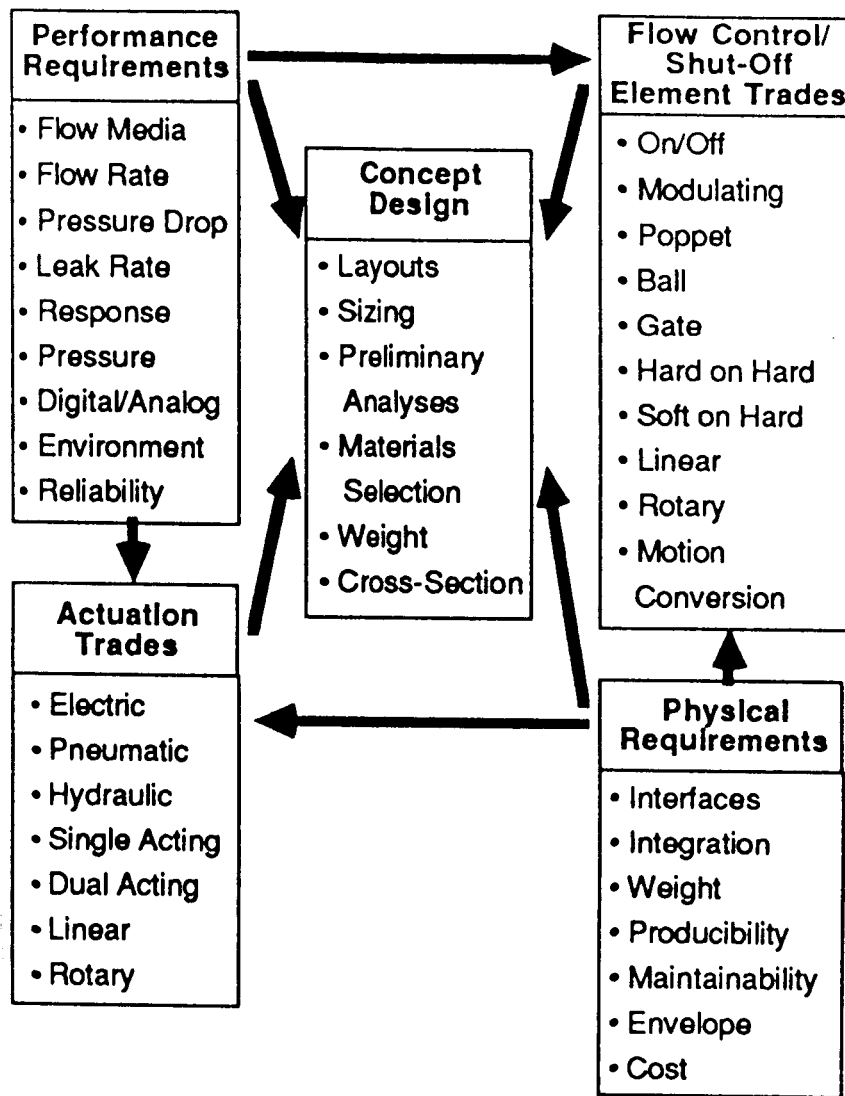


Figure 6. Interaction of Requirements and Trades Defines the Valve Concepts

II, C, Candidate Design Point Optimization (Sub-Task 2.3) (cont.)

7. Engine System Integration

The data and information provided by the conceptual design analysis of the major subcomponents is used in the development of the overall engine assembly arrangement. At this level the major elements contributing to the engine's overall life cycle cost will be examined, evaluated and their influence, in a cost sense, determined. These elements or considerations include:

a. Interfaces/Envelope/Installation

The engine concepts are evaluated as to their compliance to the interface/envelope/installation requirements. In this case an engine will pass or fail and its contribution relative to a life cycle cost value is limited.

b. Maintainability

The overall engine concept is examined for its ease of maintainability. This feature is examined at the as installed, engine assembly and component assembly level.

The maintainability of a concept will be assessed relative to the maintainability data based established on the SSME. This method allows for a quantitative assessment which can be directly used in the life cycle cost evaluation, which forms the foundation for the evaluation criteria (see Volume 2 of this document).

c. Inspectability

This feature, like maintainability, is examined at the installed engine and component assembly level.

II, C, Candidate Design Point Optimization (Sub-Task 2.3) (cont.)

Available inspection concepts are identified and assessed relative to the anticipated need. Historical data from the SSME will be used to aid in the identification of inspection needs and requirements. Using these requirements and the methods available (or expected to be available) inspectability will be assessed. Features necessary to support the inspection requirements will be identified and incorporated into the hardware conceptual designs.

After the inspection requirements and methods have been determined and an overall approach established it will be compared to the SSME and a quantitative comparative assessment made. This data will provide a basis for establishing the contribution of the inspection process to the overall life cycle cost and concept evaluation.

d. Weight

The weight of the major sub-components will be estimated and used in estimating the weight of the engine assembly. The engine weight is used to determine the impact on payload delivery capability and its resulting cost effect. This data is then used as input the evaluation process (see Volume 2 of this document).

Additionally inertia and center of gravity data will be prepared for use in establishing gimbaling requirements.

e. Gimbaling

The engine envelope and interface requirements will be evaluated relative to the engine's capability to meet the gimbaling requirements. If the requirement cannot be met changes to the engine envelope or interface will be necessary.

II, C, Candidate Design Point Optimization (Sub-Task 2.3) (cont.)

8. System Safety and Reliability

System safety, at the conceptual design level, relies on historical safety data to eliminate hazards and reduce risks. During the STME study engine designs which result in potential category I safety conditions will be rejected unless the condition can be eliminated through a design change.

Preliminary reliability predictions will be based upon previous experience with similar components or parts. If a reliability prediction indicates that the successful operation of the system is in doubt changes to the design will be made to eliminate the condition.

D. ENGINE SYSTEM TRADEOFFS AND OPTIMIZATION

The optimized engine concept is the result of an iterative process starting with the establishment of the engine/vehicle requirements. These data are used in the engine model to establish the preliminary performance and sizing of the engine and to establish the component design requirements.

The component requirements are used to conduct preliminary design and sizing analyses at the sub-component level. If an incompatibility is found with the engine level inputs, the engine model can be revised. The output from these analyses defines the major components.

An engine layout and arrangement can be prepared from these data and an engine envelope and weight determined. Interfaces are also developed and can be examined for compatibility with the original engine/vehicle interface requirements. If an inconsistency exists trade offs and refinements can be made and the component design reiterated.

At the conclusion of the process an engine concept is defined. The process is shown in Figure 7.

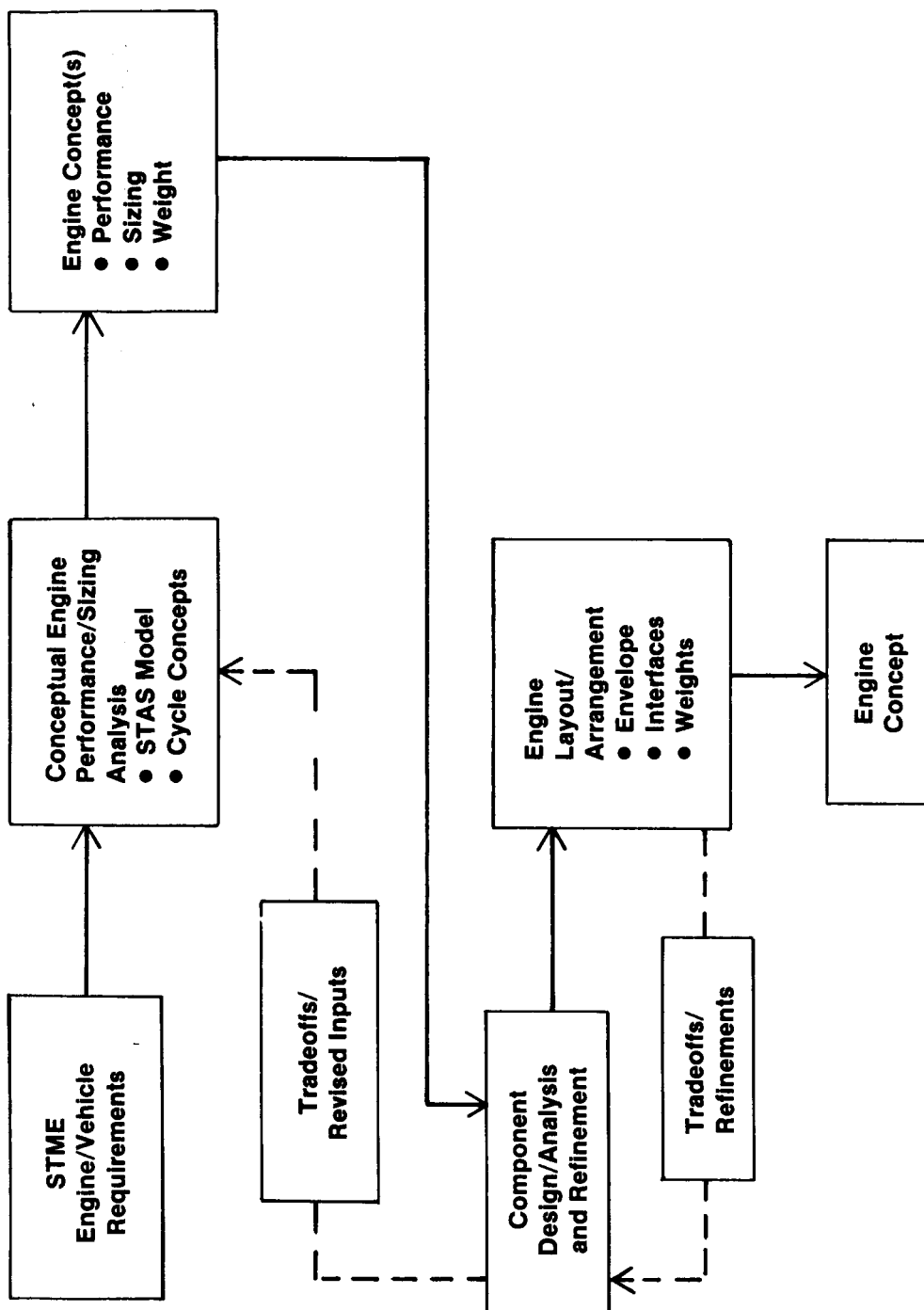


Figure 7. Engine System Tradeoff and Optimization Process